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VENTCF2: an Algorithm and Associated FORTRAN 77 Subroutine for Calculating Flow through a Horizontal Ceiling/Floor Vent in a Zone-type Compartment Fire Model

Leonard Y. Cooper

National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

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ABSTRACT

*An algorithm and associated FORTRAN 77 subroutine, called **VENTCF2**, for calculating the effects on two-layer compartment fire environments of the quasi-steady flow through a circular, shallow (i.e. small ratio of depth-to-diameter), horizontal vent connecting two spaces is presented. The two spaces can be either two inside rooms of a multi-room facility or one inside room and the outside ambient environment local to the vent. The flow is determined by consideration of standard orifice-type flows driven by cross-vent pressure differences and, when appropriate, the combined pressure- and buoyancy-driven flows which occur when the density configuration across the vent is unstable, i.e. a relatively cool, dense gas in the upper space overlays a less dense gas in the lower space. The algorithm calculates rates of flow exchange between the two spaces based on previously reported model equations. Characteristics of geometry and the instantaneous environments of the two spaces are assumed to be known and specified as inputs. Outputs calculated are the rates and properties of the vent flow at the elevation of the vent as it enters the top space from the bottom space and/or as it enters the bottom space from the top space. Rates of mass, enthalpy and products of combustion extracted by the vent flows from upper and lower layers of inside room environments and from outside ambient spaces are determined explicitly. **VENTCF2** is an advanced version of the algorithm/subroutine **VENTCF** in that it includes an improved theoretical and experimental basis. The subroutine is completely modular and it is suitable for general use in two-layer, multi-room, zone-type fire model computer codes. It has been tested numerically over a wide range of input variables and the results of some of these tests are described. Published by Elsevier Science Ltd.*

NOTATION

A_V	Area of vent
$\dot{M}_{VENT,I}$; $I = 1$ to 2	Mass flow rate of vent flow component entering space I
p_{DAT}	Datum absolute pressure
p_{HIGH}	Maximum of (p_1, p_2)
p_{LOW}	Minimum of (p_1, p_2)
$p_{REF,I}$; $I = 1, 2$	Absolute pressure in space I at reference elevation $y_{REF,I}$.
p_1 (p_2)	Absolute hydrostatic pressure in top (bottom) space at vent elevation
y_C, y_L, y_R for space I	$y_{CEIL,I}$, $y_{LAYER,I}$ and $y_{REF,I}$, respectively.
$y_{CEIL,I}$ $(y_{REF,I})$; $I = 1, 2$	If space I is inside room: elevation of ceiling (floor) of room I above datum elevation; if space I is 'outside room': $y_{CEIL,I}$ and $y_{REF,I}$ are identical and equal to reference elevation of space I above datum elevation, i.e. $y_{CEIL,I} \equiv y_{REF,I}$
$y_{LAYER,I}$; $I = 1, 2$	If space I is inside room: elevation of upper/lower layer interface in room I above datum elevation; if space I is 'outside room': $y_{LAYER,I} \equiv y_{REF,I}$
y_{VENT}	Elevation of vent above datum elevation
Δp	$p_2 - p_1$
Δp_{FLOOD}	Minimum value of $\lvert \Delta p \rvert$, in cases of unstable cross-vent density configurations, leading to uni-directional vent flow; eqn (A20) of the Appendix
$\Delta p_{FLOOD,I}$; $I = 1, 2$	Δp_{FLOOD} for onset of uni-directional flow into space I
$\delta p_{REF,I}$; $I = 1, 2$	Pressure at reference elevation, $y_{REF,I}$, in space I above datum absolute pressure, p_{DAT}; if space I is inside room, then $\delta p_{REF,I}$ and $y_{REF,I}$ correspond to pressure and elevation, respectively, within the room and at the floor
$\rho_{L,I}$ $(\rho_{U,I})$; $I = 1, 2$	If space I is inside room: density of lower (upper) layer in room I if volume of lower (upper) layer is non-zero [if lower (upper) layer volume is zero then $\rho_{L,I}$ $(\rho_{U,I})$ is not used in calculation]; if space I is 'outside room': $\rho_{L,I}$ is uniform density there and $\rho_{U,I} \equiv \rho_{L,I}$

1 INTRODUCTION

This work describes an algorithm and associated FORTRAN 77 subroutine, called ***VENTCF2***, to calculate under arbitrary conditions the instantaneous effects on two-layer fire environments of the quasi-steady flow through a horizontal vent connecting two spaces involved in a compartment fire. The subroutine is designed to be modular and easy to integrate into any two-layer zone-type compartment fire model. The algorithm ***VENTCF2***, which was developed in Cooper,[10] is based on ideas outlined in Cooper,[2] theoretical considerations of Cooper[3] and experimental data from reduced-scale hot-air/cool-air experiments[4] and salt-water/fresh-water experiments.[5,6] ***VENTCF2*** is an advanced version of the algorithm/subroutine ***VENTCF***,[2,7] which was developed without the benefit of Cooper,[3] Heskestad and Spaulding[4] and Epstein.[5] Concise, stand-alone, reference documentation of ***VENTCF2*** is presented in the Appendix.

Flow through horizontal vents is a general problem associated with ventilation of enclosed, heated/cooled spaces. It is a problem whose general solution is required, for example, if one is to be able to predict the spread of smoke (i.e. fire-heated and -contaminated air) and the flow of fresh air (i.e. oxygen, which could sustain a fire, lack of which could extinguish a fire) during fires in multi-room facilities. Reference here is to smoke spread between contiguous rooms, or between a smoky room and the outside environment, separated by a horizontal partition (i.e. ceiling/floor) with penetrations (i.e. vents), where room-to-room or room-to-outside, cross-vent, pressure differences of arbitrary magnitude and direction can be generated by forced-ventilation HVAC systems, thermal buoyancy forces (i.e. stack effect) and/or wind effects. The problem has application in fire scenarios involving top-vented atria, stairwells, ship holds, etc. The purpose for this work is to provide a computational tool that can be used to predict these phenomena.

2 THE BASIC PROBLEM

Consider the flow through a horizontal ceiling/floor vent connecting two spaces, one on top of the other, involved in a fire-generated environment. The two spaces can be two inside rooms of a multi-room facility, as depicted in Fig. A1(a) of the Appendix, or they can be comprised of one inside room of a facility and one outside space, above or below the room, which is used to simulate outside ambient conditions, local to the vent. The latter configurations are depicted in Fig. A1(b) and A1(c) of the Appendix, respectively.

When the upper gas is less dense than the lower gas, i.e. the fluid configuration is stable, the flow through the vent is determined by a traditional orifice-type flow model. Then, flow is determined by the cross-vent pressure difference without any regard for buoyancy effects (see, e.g. Emmons[8] and Cooper[9]). When the configuration is unstable and the upper gas is more dense than the lower gas, the effects of combined pressure and buoyancy forces can be significant. For example, if the cross-vent pressure is relatively small, less than the critical value, Δp_{FLOOD}, the unstable density configuration leads to an exchange-type of flow, with gas in the lower space rising into the upper space and gas from the upper space dropping into the lower space, where the flow rate from the high- to the low-pressure side of the vent is the larger of the two. Even when the cross-vent pressure difference is large enough to produce uni-directional flow, the effect of buoyancy can be great enough to reduce significantly the flow rate from what it would be in the absence of a cross-vent density difference. In the present algorithm, for the case of unstable configurations the calculation of the flow between the two spaces is based on the analysis of Cooper,[10] which uses theoretical considerations,[3] and experimental data (hot-air/cool-air in the uni-directional flow regime, flow from top to bottoms[4] and salt-water/fresh-water vent flows in the exchange-flow regimes[5,6]).

The algorithm/subroutine ***VENTCF2*** would be used to calculate the net instantaneous rates of addition of mass, enthalpy and products of combustion of interest and the properties of the vent flows to each of the two connected spaces at the elevation of the vent. A determination of where such flows go once they enter the receiving spaces would be determined with the use of additional algorithms and associated subroutines. These additional algorithms, which would use the output of the present algorithm/subroutine, would be based on considerations beyond the scope of the present work.

A flow through the horizontal vent which enters one of the spaces joined by the vent is extracted from the other space. Depending on the configuration of the two spaces, the direction of the flow and, in the case of inside rooms, the elevation of the two-layer interface (i.e. at the floor, ceiling or in-between), the present algorithm determines explicitly the rates of extraction of mass, enthalpy and products of combustion from the upper and lower layers of the one or two inside rooms and/or from an outside ambient space joined by the vent under consideration. Along with other components of flow to or from the layers of the inside rooms, determined with the use of other algorithms, these rates would be used to continue in time the solution to the equations of the overall fire model. These are the equations used to simulate mathematically the facility's overall dynamic fire environment.

3 LIMITATIONS ON VENT SHAPE

For unstable density configurations, the model of Cooper[10] and, therefore, the algorithm/subroutine presented here is for flow through a circular, shallow (i.e. small ratio of depth-to-diameter), horizontal vent. It is expected that the model will give reasonable estimates of flow even for non-circular vents, provided the aspect ratio (maximum-to-minimum span) of a vent shape of interest is not too much different than unity. Indeed, example calculations of Cooper[11] (steady burning in a ceiling-vented room), which include comparisons with some relevant experimental data, provide limited support for the applicability of the model in the case of square vents. However, when cross-vent pressure differences are small-to-moderate compared to Δp_{FLOOD}, use of the model for high-aspect-ratio and/or moderate-to-large-depth vents is not valid. Results beyond those developed in Cooper[10] are required before the present work can be evaluated for its use in predicting flows through the latter types of vent shapes.

4 THE ALGORITHMS AND ASSOCIATED FORTRAN 77 SUBROUTINES *VENTCF2* AND *VENTCF2A* FOR CALCULATING THE EFFECTS OF FLOW THROUGH HORIZONTAL CEILING/FLOOR VENTS

The algorithm ***VENTCF2*** and a listing of its associated subroutine, coded in FORTRAN 77, is presented in the Appendix (from Appendix A of Cooper[12]). The reader is also referred to Appendix B of Cooper,[12] which includes documentation and an associated subroutine for ***VENTCF2A***, a modification of ***VENTCF2***. ***VENTCF2A*** provides special considerations for 'smoothing' rates of layer extraction from the flow-source room at times of relatively thin adjacent-vent layers. When used in a full zone model, and depending on the integration software for the particular model, the considerations in ***VENTCF2A*** eliminate singularities that may cause convergence problems in fire simulations at times when adjacent-vent layers are growing or shrinking from near-zero depths.

Cooper and Forney[13] have edited a catalog of algorithms/subroutines useful for simulating the physical phenomena in multi-room zone-type compartment fire model computer codes. Pagination of Appendices A and B of Cooper[12] is such that they can be directly inserted as entries of an updated catalog.[13]

The catalog[13] was conceived of as a growing document, where the entries would be available for general use by people interested in: developing or improving, for their own particular needs, a general or special-purpose multi-room zone-type compartment fire model; or predicting isolated compartment fire phenomena, for whatever reason.

The development, technology transfer, and use of a type of catalog of these kinds[13] of algorithms and associated subroutines is enhanced by maintaining guidelines for a uniform format of algorithm/subroutine documentation. In this regard a prototype format was developed and used in all algorithm/subroutine catalog entries.[13] This format, which is followed here, includes the following elements:

TITLE	Should indicate the main purpose of the algorithm/subroutine
DESCRIPTION	General description of the algorithm
OUTPUT	List of output variables, including definitions and units
INPUT	List of input variables, including definitions and units
CALCULATIONS	Concise description of rules for obtaining output variables from input variables, including or referring explicitly to all equations required in the calculation. If other algorithms/subroutines are required, then these should be readily available and referenced
SUBROUTINES USED	Listing of or explicit reference to each algorithm/subroutine used to carry out the calculations
REFERENCES	A list of references
SUBROUTINE VARIABLES	Cross-reference of all nomenclature (including units) introduced above to nomenclature used in the FORTRAN 77 subroutine
PREPARED BY	Who prepared the algorithm/subroutine and date of preparation
SUBROUTINE	Listing of the subroutine; well-commented, including a summary of its purpose and definitions (including units) of input/output variables

5 TESTING THE SUBROUTINES

5.1 Subroutine *VENTCF2*

Extensive parametric testing of the subroutine ***VENTCF2*** has been carried out. A wide range of environment scenarios was considered for each of the three basic configurations of Fig. A1. For each configuration, parameters were varied to simulate all possible combinations of the following specifications:

(a) for the two layers of an inside space: two non-zero-thickness layers (i.e. layer interface between the ceiling and floor), or one non-zero-thickness layer and one zero-thickness layer (i.e. layer interface at the ceiling or floor);
(b) stable or unstable cross-vent density configuration;
(c) the reference elevation for an outside space is above, at, or below the vent elevation;
(d) 1 atmosphere reference pressure, $p_{\mathrm{REF},1}$, in the top space (i.e. $p_{\mathrm{DAT}} = 101\,325$ Pa with $\delta p_{\mathrm{REF},1} \equiv p_{\mathrm{REF},1} - p_{\mathrm{DAT}} = 0$) and reference pressure in the bottom space, $p_{\mathrm{REF},2}$, varying from 0.01 atmospheres to 2.0 atmospheres (i.e. $-0.99p_{\mathrm{DAT}} < \delta p_{\mathrm{REF},2} \leq p_{\mathrm{DAT}}$); and
(e) 1 atmosphere reference pressure, $p_{\mathrm{REF},2}$, in the bottom space (i.e. $p_{\mathrm{DAT}} = 101\,325$ Pa with $\delta p_{\mathrm{REF},2} \equiv p_{\mathrm{REF},2} - p_{\mathrm{DAT}} = 0$) with reference pressure in the top space, $p_{\mathrm{REF},1}$, varying from 0.01 atmospheres to 2 atmospheres (i.e. $-0.99p_{\mathrm{DAT}} < \delta p_{\mathrm{REF},1} \leq p_{\mathrm{DAT}}$).

All scenarios involved a vent area $A_V = 1\ \mathrm{m}^2$. Five elevations (relative to a datum elevation), y_N, $N = 1$ to 5, and three densities, ρ_N, $N = 1$ to 3, were required to construct the environment scenarios. These were:

$$y_1 = 0;\ y_2 = 1.5\ \mathrm{m};\ y_3 = 3\ \mathrm{m};\ y_4 = 4.5\ \mathrm{m};\ y_5 = 6\ \mathrm{m};\ \rho_1 = 1\ \mathrm{kg/m^3};$$
$$\rho_2 = 0.50\ \mathrm{kg/m^3};\ \rho_3 = 0.25\ \mathrm{kg/m^3} \tag{1}$$

When the environment of an inside room involved two layers, the layer densities were specified to be in a stable configuration (i.e. a low density layer above a high density layer).

All configurations and environment specifications used in the parametric testing of the subroutine are identified in Table 1 of Cooper.[12] This involved 162 basic Cases. Each Case involved a separate parametric study of over two thousand calls to the subroutine. These covered the pressure

TABLE 1

Configurations/Environments Used to Test the ***VENTCF2*** Subroutine (Part of Table 1 of Cooper[12]): $\rho_1 = 1\ \text{kg/m}^3 > \rho_2 = 0.50\ \text{kg/m}^3 > \rho_3 = 0.25\ \text{kg/m}^3$; $p_{DAT} = 1.01325x10^5$ Pa; $A_V = 1\ \text{m}^2$; $y_1 = 0 < y_2 = 1.5\ \text{m} < y_3 = 3\ \text{m} < y_4 = 4.5\ \text{m} < y_5 = 6\ \text{m}$

Cases 1–54: *space* 1 (*top space*) *is inside room, space* 2 (*bottom space*) *is inside room—Figure A*1(*a*) *of the Appendix*

Case no.	*Space 1*	*Space 2*	
•			
•			
•			
	Two Layer $y_R = y_3$ $y_L = y_4$ $y_C = y_5$ ↓	Two Layer $y_R = y_1$ $y_L = y_2$ $y_C = y_3$ ↓	
28			$\rho_{L,1} = \rho_2 = \rho_{U,2} < \rho_{L,2} = \rho_1$ $\delta p_{REF,2} = 0, p_{DAT} < \delta p_{REF,1} \leq p_{DAT}$
29*			$\rho_{L,1} = \rho_1 > \rho_{U,2} = \rho_2 < \rho_{L,2} = \rho_1$ $\delta p_{REF,1} = 0, p_{DAT} < \delta p_{REF,2} \leq p_{DAT}$
30*			$\rho_{L,1} = \rho_1 > \rho_{U,2} = \rho_2 < \rho_{L,2} = \rho_1$ $\delta p_{REF,2} = 0, p_{DAT} < \delta p_{REF,1} \leq p_{DAT}$
•			
•			
•			

*Unstable cross-vent density configuration.

ranges identified above in either specification d or specification e. The calls involved incremental changes of the relative reference pressures, $\delta p_{REF,1}$ for specification e and $\delta p_{REF,2}$ for specification d, which were small enough to reveal details of the exchange-flow phenomena, these being sensitive to fractional-pascal-level variations in cross-vent pressure differences.

For three of the 162 Cases studied in Cooper,[12] Cases 28–30, Table 1 (a segment of Table 1 of Cooper[12]) identifies values of the parameters which define the configuration of the two spaces, as illustrated in Fig. A1, and the states of the environments in the spaces. These are the parameters used to call the subroutine. (The reader is referred to the Notation for explanation of terms used in the table.) Also explicitly identified in the

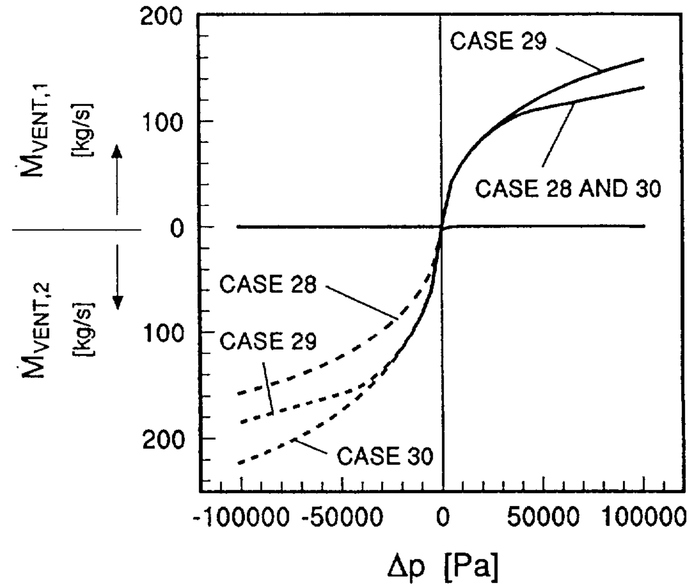

Fig. 1. Plots of the calculated mass flow rate to upper space 1, $\dot{M}_{VENT,1}$, and to lower space 2, $\dot{M}_{VENT,2}$, as functions of the computed (coarse-scale) cross-vent pressure difference, Δp, for Cases 28–30 (see Table 1).

table are those Cases which involve unstable cross-vent density configurations (Cases 29 and 30). When cross-vent pressure differences are small enough in magnitude, such Cases lead to the exchange-flow phenomena which are of particular interest.

Presented in Figs 1 and 2 are plots of the calculated mass flow rates to upper room 1, $\dot{M}_{VENT,1}$, and to lower room 2, $\dot{M}_{VENT,2}$, as functions of the computed cross-vent pressure difference, Δp, for Cases 28–30. As in eqn (A2) of ***VENTCF2***, Δp, an output variable of the subroutine, is defined as

$$\Delta p = p_2 - p_1 \tag{2}$$

where p_1 and p_2 are the pressures in the top and bottom spaces at the vent elevation (see Fig. A2).

As indicated in Table 1, Cases 28–30 involve two inside rooms where, as depicted in Fig. A1(a), both of these have an upper and a lower layer. Case 28 involves a neutrally-stable cross-vent density configuration since the density immediately above the vent (in the lower layer of room 1), $\rho_{L,1} = \rho_2 = 0.50\,\text{kg/m}^3$, is identical to the density immediately below the

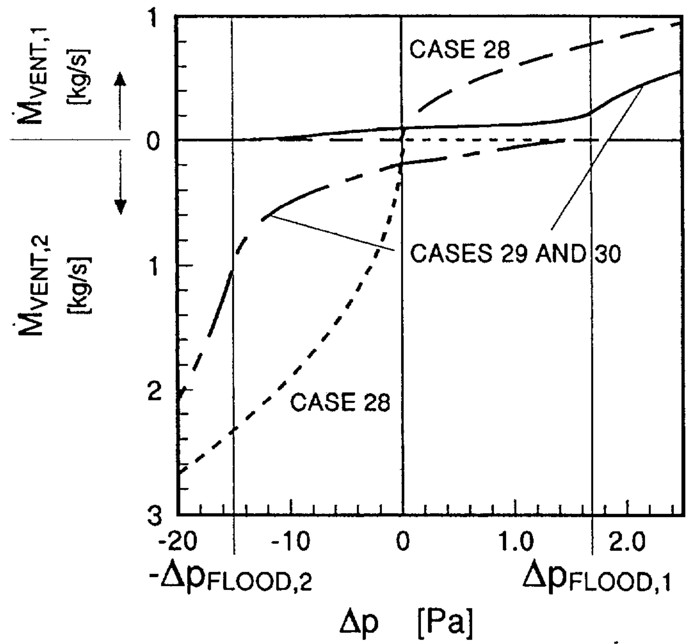

Fig. 2. Plots of the calculated mass flow rate to upper space 1, $\dot{M}_{VENT,1}$, and to lower space 2, $\dot{M}_{VENT,2}$, as functions of the computed (fine-scale) cross-vent pressure difference, Δp, for Cases 28–30 (see Table 1).

vent (in the upper layer of room 2). Cases 29 and 30 involve an unstable cross-vent density configuration since the density immediately above the vent, $\rho_{L,1} = \rho_1 = 1\ \mathrm{kg/m^3}$, is greater than the density immediately below the vent, $\rho_{U,2} = \rho_2 = 0.50\ \mathrm{kg/m^3}$.

The Δp scale of Fig. 1 is relatively coarse, and the plots reveal the calculated mass flow rates through the vent as a result of large cross-vent pressure differences, i.e. when effects of compressibility become significant, for example, for fires in nearly-hermetically-sealed facilities. In Fig. 1, the sharp breaks in the $\dot{M}_{VENT,1}$ and $\dot{M}_{VENT,2}$ plots for Cases 28 and 30 and for Case 29, respectively, correspond to cross-vent pressure differences, Δp, which separate choked from unchoked flow through the vent. Define p_{HIGH} and p_{LOW} as the absolute pressures on the high- and low-pressure side of the vent, respectively. Then, consistent with eqn (A7)–(A15), such choking occurs for air (i.e. $\gamma = 1.40$) when[9,19]

$$p_{LOW}/p_{HIGH} \leq [2/(\gamma+1)]^{\gamma/(\gamma-1)} = 0.528 \quad (3)$$

As indicated in Fig. 1, the parameters specified in Table 1 for Case 29 lead to a prediction of choked vent flow from room 1 to room 2 approximately when $\Delta p \leq -0.472 p_{DAT} = -0.478 \times 10^5\ \mathrm{Pa}$. Similarly, the parameters specified in Table 1 for Cases 28 and 30 lead to a prediction of choked vent flow from room 1 to room 2 approximately when $\Delta p \leq -0.894 p_{\mathrm{DAT}} = -0.906 \times 10^5$ Pa. Also, for Cases 28 and 30, choked flow from room 2 to room 1 is predicted when $\Delta p \geq 0.472 p_{\mathrm{DAT}} = 0.478 \times 10^5$ Pa. Finally, for Case 29, choked flow from room 2 to room 1 is predicted when $\Delta p \geq 0.894 p_{\mathrm{DAT}} = 0.906 \times 10^5$ Pa.

The Δp scale of Fig. 2 is relatively fine, and the plots reveal the calculated mass flow rates through the vent when the cross-vent pressure differences are at or close to zero. Since the Case-28 density configuration is neutrally-stable, i.e. only uni-directional or zero flow is possible, the mass flow rates through the vent corresponding to $\Delta p = 0$ are seen to be identically zero. However, for the unstable cross-vent density configurations of Cases 29 and 30, the vent flow algorithm is seen to lead to the exchange-flow phenomenon. In particular, there is a non-zero vent flow exchange between the top and bottom spaces whenever $|\Delta p| < \Delta p_{\mathrm{FLOOD}}$, where $\Delta p_{\mathrm{FLOOD}}$ is defined in eqn (A20).

5.2 Subroutine *VENTCF2A*

The subroutine ***VENTCF2A*** was found to give plausible results when tested in CCFM.VENTS[13–16] with a variety of time-dependent one- and two-room fire scenarios. Except for the small-scale, limited-regime data of Heskestad and Spaulding,[4] Epstein,[5] and Epstein and Kenton[6] which were used to develop ***VENTCF2*** and ***VENTCF2A***,[3,10] the algorithm has not been validated experimentally.

6 SUMMARY

Development and testing of the algorithm and associated FORTRAN 77 subroutine, called ***VENTCF2***, for calculating the effects on two-layer compartment fire environments of the quasi-steady flow through a circular, shallow (i.e. small ratio of depth-to-diameter), horizontal vent connecting two spaces was presented. ***VENTCF2*** can be expected to give reasonable estimates even for non-circular vents provided the aspect ratio (maximum-to-minimum span) of a vent shape of interest is not too much different from unity, e.g. for square vents. However, use of ***VENTCF2*** for high-aspect-ratio and/or moderate-to-large-depth vents is not generally valid.

The idea of a general catalog of algorithms/subroutines useful for simulating the physical phenomena in multi-room zone-type compartment fire model computer codes was introduced. For such a catalog, an overview of recommended format guidelines for stand-alone algorithm/subroutine-documentation entries was presented. Concise reference documentation of ***VENTCF*2**, conforming to these latter guidelines, is presented in the Appendix.

APPENDIX

***VENTCF*2—Calculation of the Flow Through a Horizontal Ceiling/Floor Vent Connecting Two Spaces**

DESCRIPTION

Consider an instant of time during the simulation of a multi-room compartment fire environment. This algorithm calculates the flow of mass, enthalpy, oxygen and other products of combustion through a horizontal vent located in a ceiling/floor partition common to any two inside rooms of the facility or between an inside room and the outside environment local to the vent. ***VENTCF*2**, is an advanced version of the algorithm/subroutine ***VENTCF***[1] in that it includes an improved theoretical and experimental basis.[3,10,11]

Depicted in Fig. A1(a) is the vent and the two spaces when they are both inside rooms of a multi-room facility. Figure A1(b) and A1(c) depict the situation when the two spaces involve one inside room of the facility and one outside space, either above or below the room, in which is simulated the outside environment local to the vent.

As in Fig. A1, designate the top space as space 1 and the bottom space as space 2. It is assumed that the temperature, density, concentration of oxygen and of other products of combustion of interest in the upper and lower layer of each inside room and in the environment local to the vent of an outside space are specified. Also specified in each inside room are: the elevation above the datum elevation of the floor, and the upper-layer/lower-layer interface; and the pressure at the floor above the specified datum pressure. Specified in an outside space are: a reference elevation above the datum elevation, and the pressure at this reference elevation above the specified datum pressure.

When the upper gas is less dense than the lower gas, i.e. the fluid configuration is stable, the flow through the vent is determined by a

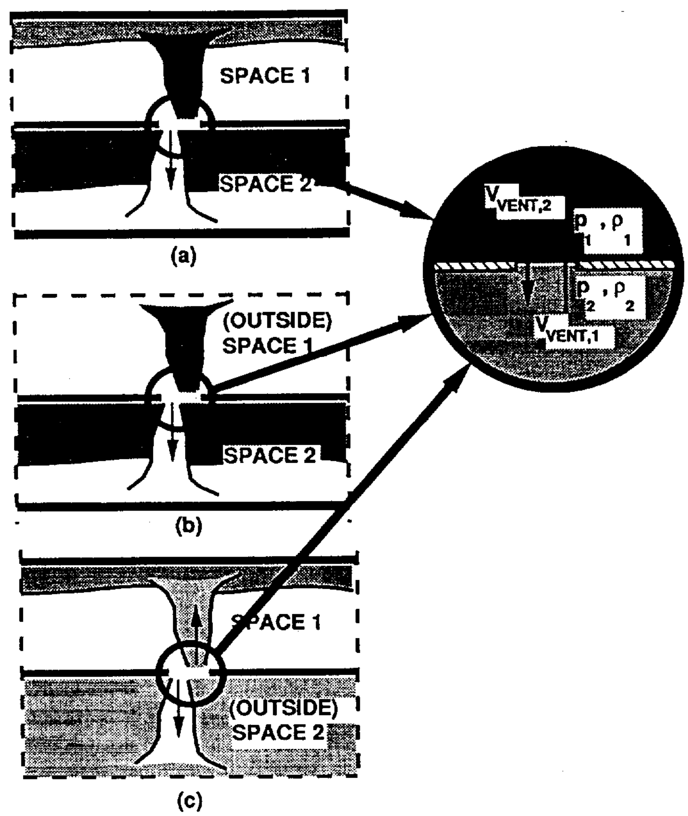

Fig. A1. The possible configurations of the two spaces joined by a horizontal ceiling/floor vent with space 1 above space 2: (a) two inside rooms; (b) an outside space above an inside room; (c) an inside room over an outside space.

traditional orifice-type flow model. Then, flow is determined by the cross-vent pressure difference without any regard for buoyancy effects (see, e.g. Emmons[8] and Cooper[9]) and the present algorithm/subroutine is identical to that of ***VENTCF***.[1] When the configuration is unstable and the upper gas is more dense than the lower gas, the effects of combined pressure and buoyancy forces can be significant. For example if the cross-vent pressure is relatively small, the unstable density configuration leads to an exchange-type of flow, with gas in the lower space rising into the upper space and gas from the upper space dropping into the lower space, where the flow rate from the high- to the low-pressure side of the vent is the larger of the two. Also, even when the cross-vent pressure difference is large enough to produce uni-directional flow, the effect of buoyancy can be great enough to reduce significantly the flow rate from what it would be in the absence of a cross-vent density difference. In the present algorithm, for the case of unstable configurations the calculation of the flow between the two spaces is based on the theory and analysis of Cooper.[3,10]

For unstable density configurations, the model of Cooper[10] and, therefore, the ***VENTCF2*** algorithm/subroutine itself is for flow through a circular, shallow (i.e. small ratio of depth to diameter), horizontal vent. It is also expected that the model will give reasonable estimates of flow even for non-circular vents, provided the aspect ratio (maximum-to-minimum span) of a vent shape of interest is not too much different from 1. Indeed, example calculations of Cooper[11] (steady burning in a ceiling-vented room), which include comparisons with some relevant experimental data, provide limited support for the applicability of the model in the case of square vents. However, use of ***VENTCF2*** in high-aspect-ratio and/or moderate-to-large-depth vent scenarios is not valid when cross-vent pressure differences are small-to-moderate compared to $\Delta p_{\mathrm{FLOOD}}$. Results beyond those developed in Cooper[10] are required before the present work can be extended and used for the latter types of vent shape.

The geometry and conditions local to the vent which determine the characteristics of the vent flow are depicted in Fig. A2. These include: the densities, ρ_1 and ρ_2, and the hydrostatic pressures, p_1 and p_2, at the elevation, but away from the immediate vicinity of the vent in the upper and lower spaces, respectively, and the area, A_{V}, and shape of the vent.

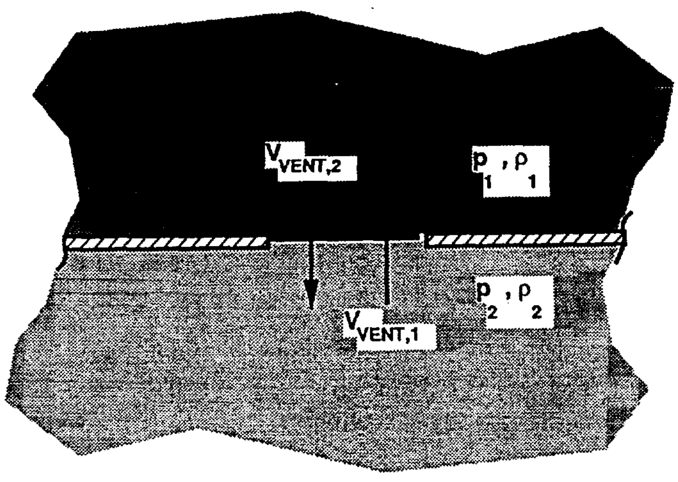

Fig. A2. The geometry and conditions local to a horizontal ceiling/floor vent which determine the characteristics of the vent flow.

Regarding the shape, at the present time results for horizontal vent flows are only available for circular or square vents. Other properties local to the vent and indicated in Fig. A2 are T_1 and T_2, the absolute temperatures, $c_{O2,1}$ and $c_{O2,2}$, the concentrations of oxygen, and $c_{K,1}$ and $c_{K,2}$, $K=2$ to N_{PROD}, the concentrations of a product of combustion K.

To simulate fire scenarios at times when vent flows are driven by arbitrarily high cross-vent pressure differences (i.e. when compressibility effects begin to be significant), whether for stable or unstable cross-vent density configurations, ***VENTCF2*** implements the ideas introduced in Cooper[9] and implemented previously in the algorithm/subroutines ***VENTHP***[17] and ***VENTCF***.[1] Such high cross-vent pressure differences could occur, for example, in fire scenarios involving flows through cracks in otherwise hermetically-sealed fire compartments.

The ***VENTCF2*** subroutine has been subjected to extensive testing in a 'stand-alone' mode.[12]

OUTPUT

$c_{O2,1}$ ($c_{O2,2}$)	Concentration of O_2 in top (bottom) space at elevation of vent [(kg O_2)/(kg layer)]
$c_{K,1}$ ($c_{K,2}$)	Concentration of product K in top (bottom) space at elevation of vent. [(unit of product K)/(kg layer)]
$c_{VENT,O2,I}$; $I=1$ or 2	Concentration of O_2 in component of vent flow entering space I, provided such vent flow component is non-zero, i.e. provided $\dot{M}_{VENT,I}$ is non-zero [(kg O_2)/(kg vent flow)]
$c_{VENT,K,I}$; $I=1$ or 2; $K=2$ to N_{PROD}	Concentration of product of combustion K in component of vent flow entering space I, provided such vent flow component is non-zero, i.e. provided $\dot{M}_{VENT,I}$ is non-zero [(unit of product)/(kg vent flow)]
$\dot{M}_{L,I}$ ($\dot{M}_{U,I}$); $I=1$ or 2	If space I is an inside room: rate at which mass is *added* to lower (upper) layer of room I due to vent flow component which enters the other space. Note that this will *always be negative*, since layer which supplies the material flowing to the other space will always have mass *extracted* from it [kg/s];

	If space I is an 'outside room': $\dot{M}_{U,I}$ is rate at which mass is *added* to space I due to vent flow component which enters the other space (i.e. the inside room). Note that this will *always be negative*, since an outside space which supplies material flowing through the vent to an adjacent space will always have mass *extracted* from it. $\dot{M}_{L,I}$ is identical to $\dot{M}_{U,I}$ [kg/s]
$\dot{M}_{VENT,I}$; $I = 1$ to 2	Mass flow rate of vent flow component entering space I [kg/s]
$\dot{P}_{O2,L,I}$ ($\dot{P}_{O2,U,I}$); $I = 1$ or 2	If space I is an inside room: rate at which O_2 is *added* to lower (upper) layer of room I due to vent flow component which enters the other space. Note that this will *always be negative*, since the layer which supplies the material flowing through the vent to the other space will always have its convected O_2 *extracted* from it [(kg O_2)/s]; If space I is an 'outside room': $\dot{P}_{O2,U,I}$ is rate at which O_2 is *added* to space I due to the vent flow component which enters the other space (i.e. the inside room). Note that this will *always be negative*, since an outside space which supplies material flowing through the vent to an adjacent space will always have its convected O_2 *extracted* from it. $\dot{P}_{O2,L,I}$ is identical to $\dot{P}_{O2,U,I}$ [(kg O_2)/s]
$\dot{P}_{O2,VENT,I}$; $I = 1$ to 2	Mass flow rate of O_2 of vent flow component entering space I [(kg O_2)/s]
$\dot{P}_{K,L,I}$ ($\dot{P}_{K,U,I}$); $K = 2$ to N_{PROD}; $I = 1$ or 2	If space I is an inside room: rate at which product of combustion K is *added* to lower (upper) layer of room I due to vent flow component which enters the other space. Note that this will *always be negative* since the layer which supplies the material flowing through the vent to the other space will always have its convected product K *extracted* from it [(unit of product K)/s]; If space I is an 'outside room': $\dot{P}_{K,U,I}$ is the rate at which product K is *added* to space I due to vent flow component entering the other space (i.e. the

inside room). Note: this will *always be negative*, since an outside space which supplies material flowing through the vent to an adjacent space will always have the convected product K *extracted* from it. $\dot{P}_{K,L,I}$ is identical to $\dot{P}_{K,U,I}$ [(unit of product K)/s]

$\dot{P}_{K,\mathrm{VENT},I}$; $I = 1$ to 2; $K = 2$ to N_{PROD}	Flow rate of product of combustion K in vent flow component entering space I [(unit of product K)/s]
p_1 (p_2)	Absolute hydrostatic pressure in the top (bottom) space at the elevation of the vent [$\mathrm{Pa} = \mathrm{kg/(m \cdot s^2)}$]
$\dot{Q}_{L,I}$ ($\dot{Q}_{U,I}$); $I = 1$ or 2	If space I is an inside room: rate at which enthalpy is *added* to lower (upper) layer of room I due to vent flow component which enters the other space. Note that this will *always be negative*, since the layer which supplies the material which flows to the other space will always have its convected enthalpy *extracted* from it. The enthalpy is based on the absolute temperature of the flow, $T_{\mathrm{VENT},I}$ [W]; If space I is an 'outside room': $\dot{Q}_{U,I}$ is the rate at which enthalpy is *added* to space I due to vent flow component which enters the other space (i.e. the inside room). Note that this will *always be negative*, since an outside space which supplies material which flows through the vent to an adjacent space will always have its convected enthalpy *extracted* from it. The enthalpy is based on the absolute temperature of the flow, $T_{U,I}$. $\dot{Q}_{L,I}$ is identical to $\dot{Q}_{U,I}$ [W]
$\dot{Q}_{\mathrm{VENT},I}$; $I = 1$ to 2	Total enthalpy flow rate in vent flow component entering space I, based on absolute temperature of the flow, $T_{\mathrm{VENT},I}$ [W]
T_1 (T_2)	Absolute temperature in top (bottom) space at elevation of the vent [K]
$T_{\mathrm{VENT},I}$; $I = 1$ to 2	Absolute temperature of vent flow component entering space I, provided such flow is non-zero [K]

Δp — $p_2 - p_1$, i.e. difference between pressure in the bottom space at elevation of the vent, and pressure in top space at elevation of the vent [Pa = kg/(m·s²)]

ρ_1 (ρ_2) — Density in top (bottom) space at the elevation of the vent [kg/m³]

$\rho_{\mathrm{VENT},I}$; $I = 1$ to 2 — Density of vent flow component entering space I, provided such vent flow is non-zero [kg/m³]

INPUT

A_{V} — Area of vent [m²]

$c_{\mathrm{L},K,I}$ ($c_{\mathrm{U},K,I}$); $K = 2$ to N_{PROD}; $I = 1$ or 2 — If space I is inside room: concentration of product of combustion K in lower (upper) layer of room I if the volume of the lower (upper) layer is non-zero [if the lower (upper) layer volume is zero then the $c_{\mathrm{L},K,I}$ ($c_{\mathrm{U},K,I}$) value is not used in the calculation], [(unit of product K)/(kg layer)];
If space I is an 'outside room': $c_{\mathrm{L},K,I}$ is the uniform concentration throughout the space of product K; $c_{\mathrm{U},K,I}$ is specified as being identical to $c_{\mathrm{L},K,I}$ [(unit of product K)/(kg local atmosphere)]

$c_{\mathrm{L,O2},I}$ ($c_{\mathrm{U,O2},I}$); $I = 1$ or 2 — If space I is inside room: concentration of O_2 in lower (upper) layer of room I if the volume of the lower (upper) layer is non-zero [if the lower (upper) layer volume is zero then the $c_{\mathrm{L,O2},I}$ ($c_{\mathrm{U,O2},I}$) value is not used in the calculation], [(kg O_2)/(kg layer)];
If space I is an 'outside room': $c_{\mathrm{L,O2},I}$ is the uniform concentration throughout the space of O_2; $c_{\mathrm{U,O2},I}$ is specified as being identical to $c_{\mathrm{L,O2},I}$ [(kg O_2)/(kg local atmosphere)]

C_{p} — Specific heat at constant pressure of the vent flow [W·s/(kg·K)] (suggest 10^3 W·s/(kg·K) for air as default)

N_{PMAX} — Maximum allowed number of products of combustion

N_{PROD} — Number of products of combustion, including O_2, being tracked in the simulation

p_{DAT} — Datum absolute pressure $[\mathrm{Pa} = \mathrm{kg}/(\mathrm{m}\cdot\mathrm{s}^2)]$

$T_{L,I}$ ($T_{U,I}$); $I = 1$ or 2 — If space I is inside room: absolute temperature of lower (upper) layer in room I, if volume of the lower (upper) layer is non-zero [if lower (upper) layer volume is zero then $T_{L,I}$ ($T_{U,I}$) value is not used in the calculation], [K];
If space I is 'outside room': $T_{L,I}$ is the uniform absolute temperature there, taken to be the temperature at the reference elevation, $y_{REF,I}$; $T_{U,I}$ is specified as being identical to $T_{L,I}$ [K]

$y_{CEIL,I}$ ($y_{REF,I}$) — If space I is inside room: elevation of ceiling (floor) of room I above datum elevation [m];
If space I is 'outside room': $y_{CEIL,I}$ and $y_{REF,I}$ are both identical and equal to the reference elevation of space I above the datum elevation, i.e. the specification must satisfy $y_{CEIL,I} \equiv y_{REF,I}$. The latter identity, which will never be satisfied for an inside room, is a characteristic of the input data used to distinguish an inside room from an 'outside room' [m]

$y_{LAYER,I}$; $I = 1$ or 2 — If space I is inside room: elevation of the upper/lower layer interface in room I above the datum elevation [m];
If space I is 'outside room': $y_{LAYER,I}$ is specified as being identical to $y_{REF,I}$ [m]

y_{VENT} — Elevation of vent above datum elevation. Note that y_{VENT} must be identical to either $y_{CEIL,I}$ or $y_{REF,I}$ for each of the one or two inside rooms involved in the calculation [m]

$\delta p_{REF,I}$; $I = 1$ or 2 — Pressure at reference elevation, $y_{REF,I}$, in space I above the datum absolute pressure, p_{DAT}. If space I is an inside room, then $\delta p_{REF,I}$ and $y_{REF,I}$ must correspond to the pressure and elevation, respectively, within the the room and at the floor $[\mathrm{Pa} = \mathrm{kg}/(\mathrm{m}\cdot\mathrm{s}^2)]$

ε_p — Error tolerance for $\delta p_{\mathrm{REF},I}$. If $p_{\mathrm{ERROR},I}$ is defined as the uncertainty in $\delta p_{\mathrm{REF},I}$, $I=1$ or 2, then $|p_{\mathrm{ERROR},I}| < \varepsilon_p p_0 + |\delta p_{\mathrm{REF},I}|\varepsilon_p$ where $p_0 = 1$ Pa. The first term is based on an absolute error tolerance and dominates the above error bound when $|\delta p_{\mathrm{REF},I}|$ is less than 1 Pa. The second term is a relative error tolerance and dominates when $|\delta p_{\mathrm{REF},I}|$ is greater than 1 Pa. ε_p should be chosen to be consistent with the tolerance specified for the computation of $\delta p_{\mathrm{REF},I}$ terms in the overall compartment fire model computer code which uses this algorithm.

$\rho_{\mathrm{L},I}$ ($\rho_{\mathrm{U},I}$); $I=1$ or 2 — If space I is inside room: density of lower (upper) layer in room I, if the volume of the lower (upper) layer is non-zero [if lower (upper) layer volume is zero, $\rho_{\mathrm{L},I}$ ($\rho_{\mathrm{U},I}$) is not used in the calculation], [kg/m^3];
If space I is 'outside room': $\rho_{\mathrm{L},I}$ is the uniform density there; $\rho_{\mathrm{U},I}$ is specified as identical to $\rho_{\mathrm{L},I}$ [kg/m^3]

CALCULATION

1. Calculate p_I for $I=1$ and 2, and Δp (the p_I calculation follows the ***DELP*** algorithm/subroutine of Cooper and Forney[18]):

$$p_I = \delta p_{\mathrm{REF},I} + \delta p_I + p_{\mathrm{DAT}} \tag{A1}$$

$$\Delta p = p_2 - p_1 = (\delta p_{\mathrm{REF},2} - \delta p_{\mathrm{REF},1}) + (\delta p_2 - \delta p_1) \tag{A2}$$

where g, the acceleration of gravity, is 9.8 m/s^2 and

$$\begin{aligned}&\text{if } y_{\mathrm{REF},I} \le y_{\mathrm{VENT}} \le y_{\mathrm{LAYER},I} \text{ then: } \delta p_I = -\rho_{\mathrm{L},I}\, g(y_{\mathrm{VENT}} - y_{\mathrm{REF},I})\\ &\text{else: } \delta p_I = -\rho_{\mathrm{L},I}\, g(y_{\mathrm{LAYER},I} - y_{\mathrm{REF},I}) - \rho_{\mathrm{U},I}\, g(y_{\mathrm{VENT}} - y_{\mathrm{LAYER},I})\end{aligned} \tag{A3}$$

2. Calculate ρ_I, T_I, $c_{\mathrm{O2},I}$ and the $c_{K,I}$, $K=2$ to N_{PROD}, for $I=1$ and 2, and then $\Delta\rho$:

$$\begin{aligned}&\text{if } \{[(y_{\mathrm{VENT}} = y_{\mathrm{REF},I}) \text{ and } (y_{\mathrm{LAYER},I} = y_{\mathrm{REF},I})]\\ &\text{or } [(y_{\mathrm{VENT}} = y_{\mathrm{CEIL},I}) \text{ and } (y_{\mathrm{LAYER},I} < y_{\mathrm{CEIL},I})]\}\\ &\text{then: } \rho_I = \rho_{\mathrm{U},I},\ T_I = T_{\mathrm{U},I},\ c_{\mathrm{O2},I} = c_{\mathrm{U,O2},I} \text{ and } c_{K,I} = c_{\mathrm{U},K,I}\\ &\text{else: } \rho_I = \rho_{\mathrm{L},I},\ T_I = T_{\mathrm{L},I},\ c_{\mathrm{O2},I} = c_{\mathrm{L,O2},I} \text{ and } c_{K,I} = c_{\mathrm{L},K,I}\end{aligned} \tag{A4}$$

$$\Delta\rho = \rho_1 - \rho_2 \tag{A5}$$

3. Define $\dot{V}_{ST,HIGH}$ as the volume rate of flow through the vent, from the high- to the low-pressure space, that is predicted with a 'standard', uni-directional-flow-type calculation (i.e. without regard to the effect of buoyancy, in general, or the stability of the cross-vent density configuration, in particular), where arbitrarily high cross-vent pressures are allowed. Here, the calculation follows the model of Cooper[9] as implemented in the ***VENTHP*** algorithm/subroutine of Cooper and Forney.[17] Calculate $\dot{V}_{ST,HIGH}$:

If $\Delta p = 0$ then: set $\dot{V}_{ST,HIGH} = 0$ and skip to (the next) item 4 of the CALCULATION (A6)

else ($\Delta p > 0$ or $\Delta p < 0$ and):

a. Define and compute ρ_{HIGH}, ε and x:
If $\Delta p > 0$, i.e. 'standard' flow from (lower) space 2 to (upper) space 1, then:

$$\rho_{HIGH} = \rho_2;\ \varepsilon = \Delta p / p_2 \tag{A7}$$

else [$\Delta p < 0$ and 'standard' flow from (upper) space 1 to (lower) space 2]:

$$\rho_{HIGH} = \rho_1;\ \varepsilon = -\Delta p / p_1 \tag{A8}$$

$$x = 1 - \varepsilon \tag{A9}$$

b. Compute $C(x)$, the vent flow coefficient, and $w(x)$:

$$C(x) = 0.85 - 0.25x = 0.60 + 0.25\varepsilon \tag{A10}$$

$$w(x) = \begin{cases} 1 - [3/(4\gamma)]\varepsilon \text{ if } 0 < \varepsilon \leq 10^{-5} \\ f(x)/[2\varepsilon]^{1/2} \text{ if } 1 \geq \varepsilon > 10^{-5} \end{cases} \tag{A11}$$

where

$$f(x) = \begin{cases} \{[2\gamma/(\gamma-1)]x^{2/\gamma}[1 - x^{(\gamma-1)/\gamma}]\}^{1/2} & \text{if } \varepsilon < 1 - [2/(\gamma+1)]^{\gamma/(\gamma-1)} \\ \{\gamma[2/(\gamma+1)]^{(\gamma+1)/(\gamma-1)}\}^{1/2} & \text{if } \varepsilon \geq 1 - [2/(\gamma+1)]^{\gamma/(\gamma-1)} \end{cases} \tag{A12}$$

and where γ, the ratio of specific heats of the vent flow gas, is taken to be that of air, 1.40. Note that for the present horizontal vent application, the $C(x)$ of eqn (A10) is taken to be consistent with the standard incompressible limit for flow through circular sharp-edged orifices[19] in the sense that $C \to 0.60$ as $\varepsilon \to 0$

c. Define and compute $\Delta p_{CUT}{}^{1/2}$:

$$\Delta p^{1/2}{}_{CUT} \equiv [\varepsilon_p \text{MAX}(1.0\text{ Pa}, |\delta p_{REF,1}|, |\delta p_{REF,2}|)]^{1/2} \tag{A13}$$

d. Define and compute F_{NOISE}, a numerical damping factor, and then $\dot{V}_{\mathrm{ST,HIGH}}$:

$$F_{\mathrm{NOISE}} = 1.0 - \exp(-|\Delta p|^{1/2}/\Delta p^{1/2}{}_{\mathrm{CUT}}) \tag{A14}$$

$$\dot{V}_{\mathrm{ST,HIGH}} = F_{\mathrm{NOISE}} C(x) w(x) (2/\rho_{\mathrm{HIGH}})^{1/2} A_{\mathrm{V}} |\Delta p|^{1/2} \tag{A15}$$

F_{NOISE} is designed to damp out numerical noise (error) in Δp that would otherwise be dominant in eqn (A15) when Δp is small relative to the maximum of 1 Pa and the calculated reference pressures, $\delta p_{\mathrm{REF,1}}$, $\delta p_{\mathrm{REF,2}}$. Δp_{CUT} is an estimate of how small the maximum of $|\Delta p|$ must be to retain a few digits of accuracy in Δp. When calculated $|\Delta p|$ is smaller than p_{CUT}, this value and, therefore, the value of $\dot{V}_{\mathrm{ST,HIGH}}$ in eqn (A15) will likely contain noise which should be damped. F_{NOISE} approaches 1, when $|\Delta p|$ is large relative to Δp_{CUT}, and 0, when $|\Delta p|$ is small relative to Δp_{CUT}.

4. When the cross-vent density configuration is unstable ($\Delta\rho > 0$), mixed pressure- and buoyancy-driven aspects of the flow have to be considered and the vent flow rates are calculated according to Cooper.[10] Define $\dot{V}_{\mathrm{B,HIGH}}$, $\dot{V}_{\mathrm{B,LOW}}$ as the buoyancy-affected, volume flow rates across the vent from the high-to-low and low-to-high pressure spaces, respectively.

If $\Delta\rho \leq 0$, then:

set $\dot{V}_{\mathrm{B,HIGH}} = \dot{V}_{\mathrm{B,LOW}} = 0$ and skip to item 5 of the CALCULATION (A16)

else:

a. Using the work of Hilsenrath *et al.*,[20] calculate T, $\bar{\rho}$, $\mu(T)$ in m^2/s and $\varepsilon > 0$:

$$\begin{aligned} &T = (T_1 + T_2)/2; \ \bar{\rho} = (\rho_1 + \rho_2)/2; \\ &\mu(T) = \bar{\rho}[0.04128(10^{-7})T^{5/2}/(T + 110.4)]; \ \varepsilon = \Delta\rho/\bar{\rho} > 0 \end{aligned} \tag{A17}$$

b. Calculate D and Gr; if $p_2 > p_1$, i.e. $\Delta p > 0$, then replace ε by $-\varepsilon < 0$:

$$D = (4A_{\mathrm{V}}/\pi)^{1/2}; \ Gr = 2gD^3|\varepsilon|/[\mu(T)/\bar{\rho}]^2; \text{ if } \Delta p > 0 \text{ then } \varepsilon = -\varepsilon \tag{A18}$$

c. Calculate conditions at the limit of uni-directional flow (i.e. the flooding condition) and the relative pressure, δp^*:

$$\begin{aligned} \dot{V}_{\mathrm{HIGH,FLOOD}} &= 0.1754 A_{\mathrm{V}} (2gD|\varepsilon|)^{1/2} \exp(0.5536\varepsilon); \\ \Delta p_{\mathrm{FLOOD}} &= 0.2427(4g\Delta\rho D)(1 + \varepsilon/2)\exp(1.1072\varepsilon); \\ \delta p^* &= |\Delta p|/\Delta p_{\mathrm{FLOOD}} \end{aligned} \tag{A19}$$

d. Calculate σ_1, σ_2 and then $V_{B,LOW}$, $V_{B,HIGH}$:

$$\sigma_1 = F_{NOISE}C(x)w(x)/0.1780;\ \sigma_2 = 1.045 \tag{A20}$$

If $\delta p^* \geq 1$, expect uni-directional flow:

$$V_{B,LOW} = 0;\ \dot{V}_{B,HIGH} = \dot{V}_{HIGH,FLOOD}\{1 - \sigma^2{}_2 + [\sigma^4{}_2 + \sigma^2{}_1(\delta p^* - 1)]^{1/2}\} \tag{A21}$$

else expect mixed flow:

$$\dot{V}_{EX,MAX} = 0.055(4/\pi)A_V(gD|\varepsilon|)^{1/2};\ m_3 = -0.7070;\quad M = (\sigma_1/\sigma_2)^2 - 1 \tag{A22}$$

$$\dot{V}_{B,LOW} = \dot{V}_{EX,MAX}[(1 + m_3/2)(1 - \delta p^*)^2 - (2 + m_3/2)(1 - \delta p^*)]^2$$

$$\dot{V}_{B,HIGH} = \dot{V}_{B,LOW} + \{M - [1 + (M^2 - 1)(1 - \delta p^*)]^{1/2}\}\dot{V}_{HIGH,FLOOD}/(M - 1) \tag{A23}$$

[Note: σ_1 of eqn (A20) is somewhat different from σ_1 of Cooper.[10] The modification here provides for an analytic representation of vent flow which is continuous and uniformly valid even as δp^* is increased to a level where compressibility effects become important. The result of Cooper[10] does not include the effect of compressibility.]

5. Following Cooper,[10] when $\Delta\rho > 0$ the above is taken as the flow solution provided $Gr \geq 2 \times 10^7$. For smaller Gr, the Cooper solution begins to lose its validity, since there is no existing model for $0 < Gr < 2 \times 10^7$. However, it is clear that the above-calculated 'standard' flow must be approached as $Gr \to 0$. Consistent with this, when $0 \leq Gr < 2 \times 10^7$ the vent flow is estimated by:

$$\text{flow} = (\text{'standard' flow}) + [(\text{Cooper}^{10}\ \text{flow}) - (\text{'standard' flow})]Gr/[2(10^7)]$$

a. Define $\dot{V}_{HIGH}$ and $\dot{V}_{LOW}$ as the volume flow rates across the vent from the high-to-low and low-to-high pressure spaces, respectively.

$$\text{If } \Delta\rho \leq 0 \text{ then: } \dot{V}_{HIGH} = \dot{V}_{ST,HIGH};\ \dot{V}_{LOW} = 0 \tag{A24}$$

If $\Delta\rho > 0$ and $0 < Gr < 2 \times 10^7$ then:

$$\dot{V}_{HIGH} = \dot{V}_{ST,HIGH} + (\dot{V}_{B,HIGH} - \dot{V}_{ST,HIGH})Gr/[2(10^7)];\quad \dot{V}_{LOW} = \dot{V}_{B,LOW}Gr/[2(10^7)] \tag{A25}$$

If $\Delta\rho > 0$ and $Gr \geq 2 \times 10^7$ then: $\dot{V}_{HIGH} = \dot{V}_{B,HIGH}$; $\dot{V}_{LOW} = \dot{V}_{B,LOW}$ (A26)

b. Define and calculate $\dot{V}_{\mathrm{VENT},I}$, $I=1$ and 2, the vent volume flow rate entering space I.

$$\text{If } \Delta p \geq 0 \text{ then: } \dot{V}_{\mathrm{VENT},1}=\dot{V}_{\mathrm{HIGH}};\ \dot{V}_{\mathrm{VENT},2}=\dot{V}_{\mathrm{LOW}} \tag{A27}$$

(i.e. flow to the upper space is the flow from the high- to the low-pressure space, and flow to the lower space is the flow from the low- to the high-pressure space)

$$\text{If } \Delta \mathrm{p} < 0 \text{ then: } \dot{V}_{\mathrm{VENT},1}=\dot{V}_{\mathrm{LOW}};\ \dot{V}_{\mathrm{VENT},2}=\dot{V}_{\mathrm{HIGH}} \tag{A28}$$

(i.e. flow to the upper space is the flow from the low- to the high-pressure space, and flow to the lower space is the flow from the high- to the low-pressure space)

6. Calculate the vent flow properties $\rho_{\mathrm{VENT},I}$, $T_{\mathrm{VENT},I}$, $c_{\mathrm{VENT,O2},I}$, $c_{\mathrm{VENT},K,I}$, $K=2$ to N_{PROD}, $I=1$ and 2:

$$\begin{gathered}\rho_{\mathrm{VENT},1}=\rho_2(p_1/p_2),\ \rho_{\mathrm{VENT},2}=\rho_1(p_2/p_1);\\ T_{\mathrm{VENT},1}=T_2,\ T_{\mathrm{VENT},2}=T_1;\\ c_{\mathrm{VENT,O2},1}=c_{\mathrm{O2},2}, c_{\mathrm{VENT,O2},2}=c_{\mathrm{O2},1};\\ c_{\mathrm{VENT},K,1}=c_{K,2},\ c_{\mathrm{VENT},K,2}=c_{K,1}\end{gathered} \tag{A29}$$

7. Calculate the vent flow rates $\dot{M}_{\mathrm{VENT},I}$, $I=1$ and 2:

$$\dot{M}_{\mathrm{VENT},I}=\rho_{\mathrm{VENT},I}\dot{V}_{\mathrm{VENT},I} \tag{A30}$$

8. Calculate the vent flow rates $\dot{Q}_{\mathrm{VENT},I}$, $\dot{P}_{\mathrm{O2,VENT},I}$, $\dot{P}_{K,\mathrm{VENT},I}$, $\mathrm{K}=2$ to N_{PROD}, $I=1$ and 2:

$$\begin{gathered}\dot{Q}_{\mathrm{VENT},I}=\dot{M}_{\mathrm{VENT},I}C_{\mathrm{p}}T_{\mathrm{VENT},I};\ \dot{P}_{\mathrm{O2,VENT},I}=\dot{M}_{VENT,\mathrm{I}}c_{VENT,O2,\mathrm{I}};\\ \dot{\mathrm{P}}_{\mathrm{K,VENT},I}=\dot{M}_{\mathrm{VENT},I}c_{\mathrm{VENT},K,I}\end{gathered} \tag{A31}$$

9. Calculate rates of flow added to layers of each space as a result of the vent flow extracted from it. First consider space 1 ($I=1$, $J=2$) and then space 2 ($I=2$, $J=1$). For either case:
If $\{[(y_{\mathrm{VENT}}=y_{\mathrm{REF},J})$ and $(y_{\mathrm{LAYER},I}=y_{\mathrm{REF},I})]$ or $[(y_{\mathrm{VENT}}=y_{\mathrm{CEIL},I})$ and $(y_{\mathrm{LAYER},I}<y_{\mathrm{CEIL},I})]\}$ (i.e. flow to room J is from upper layer of room I and, if space I is an inside room, its lower layer is unchanged), then:

$$\begin{gathered}\dot{M}_{\mathrm{U},I}=-\dot{M}_{\mathrm{VENT},J},\ \dot{M}_{\mathrm{L},I}=0;\ \dot{Q}_{\mathrm{U},I}=-\dot{Q}_{\mathrm{VENT},J},\ \dot{Q}_{\mathrm{L},I}=0;\\ \dot{P}_{\mathrm{O2,U},I}=-\dot{P}_{\mathrm{O2,VENT},J},\ \dot{P}_{\mathrm{O2,L},I}=0;\ \dot{P}_{K,\mathrm{U},I}=-\dot{P}_{K,\mathrm{VENT},J},\ \dot{P}_{K,\mathrm{L},I}=0\end{gathered} \tag{A32}$$

If $y_{\mathrm{REF},I} = y_{\mathrm{CEIL},I}$ (i.e. space I is an outside space), modify the results of eqn (A32) as follows:

$$\dot{M}_{\mathrm{L},I} = \dot{M}_{\mathrm{U},I};\ \dot{Q}_{\mathrm{L},I} = \dot{Q}_{\mathrm{U},I};\ \dot{P}_{\mathrm{O2,L},I} = \dot{P}_{\mathrm{O2,U},I};\ \dot{P}_{K,\mathrm{L},I} = \dot{P}_{K,\mathrm{U},I} \quad \text{(A33)}$$

If the condition above eqn (A32) is not satisfied (i.e. flow to room J is from the lower layer of room I and, if space I is an inside room, its upper layer is unchanged), then:

$$\begin{gathered}\dot{M}_{\mathrm{L},I} = -\dot{M}_{\mathrm{VENT},J},\ \dot{M}_{\mathrm{U},I} = 0;\ \dot{Q}_{\mathrm{L},I} = -\dot{Q}_{\mathrm{VENT},J},\ \dot{Q}_{\mathrm{U},I} = 0;\\ \dot{P}_{\mathrm{O2,L},I} = -\dot{P}_{\mathrm{O2,VENT},J},\ \dot{P}_{\mathrm{O2,U},I} = 0;\ \dot{P}_{K,\mathrm{L},I} = -\dot{P}_{K,\mathrm{VENT},J}, \dot{P}_{K,\mathrm{U},I} = 0\end{gathered} \quad \text{(A34)}$$

If $y_{\mathrm{REF},I} = y_{\mathrm{CEIL},I}$ (i.e. space I is an outside space), modify the results of eqn (A34) as follows:

$$\dot{M}_{\mathrm{U},I} = \dot{M}_{\mathrm{L},I};\ \dot{Q}_{\mathrm{U},I} = \dot{Q}_{\mathrm{L},I};\ \dot{P}_{\mathrm{O2,U},I} = \dot{P}_{\mathrm{O2,L},I};\ \dot{P}_{K,\mathrm{U},I} = \dot{P}_{K,\mathrm{L},I} \quad \text{(A35)}$$

SUBROUTINE VARIABLES

All nomenclature in the subroutine are identical to the nomenclature used above except for:

Above	Subroutine
A_{V}	AVENT [m^2]
C	COEF
C_{p}	CP [W·s/(kg·K)]
$c_{\mathrm{L},K,I}$, $c_{\mathrm{U},K,I}$	CONL(K,I), CONU(K,I), I = 1 or 2 [(unit of product K)/(kg layer)]
$c_{\mathrm{L,O2},I}$, $c_{\mathrm{U,O2},I}$	CONL(1,I), CONU(1,I), I = 1 or 2 [(kg O_2)/(kg layer)]
$c_{\mathrm{VENT},K,I}$	CVENT(K,I), I = 1 or 2 [(unit of product K)/(kg vent flow)
$c_{\mathrm{VENT,O2},I}$	CVENT(1,I), I = 1 or 2 [(kg O_2)/(kg vent flow)]
$c_{\mathrm{K},I}$	C(K,I), I = 1 or 2 [(unit of product K)/(kg vent flow)
$c_{\mathrm{O2},I}$	C(1,I), I = 1 or 2 [(kg O_2)/(kg vent flow)]
F_{NOISE}	FNOISE [dimensionless]
f	FF [dimensionless]

Gr	GR [dimensionless]
g	9.8 m/s^2
M	XM [dimensionless]
$\dot{M}_{L,I}$, $\dot{M}_{U,I}$	XML(I), XMU(I), I = 1 or 2 [kg/s]
$\dot{M}_{VENT,I}$	XMVENT(I), I = 1 or 2 [kg/s]
m_3	XM3 [dimensionless]
N_{PMAX}	NPMAX [dimensionless]
N_{PROD}	NPROD [dimensionless]
$\dot{P}_{K,L,I}$, $\dot{P}_{K,U,I}$	PL(K,I), PU(K,I), I = 1 or 2 [(unit of product K)/s]
$\dot{P}_{K,VENT,I}$	PVENT(K,I), I = 1 or 2 [(unit of product K)/s]
$\dot{P}_{O2,L,I}$, $\dot{P}_{O2,U,I}$	PL(1,I), PU(1,I), I = 1 or 2 [(kg O_2)/s]
$\dot{P}_{O2,VENT,I}$	PVENT(1,I), I = 1 or 2 [(kg O_2)/s]
p_{DAT}	PDATUM [Pa = kg/(m·s^2)]
p_I	P(I), I = 1 or 2 [Pa = kg/(m·s^2)]
$\dot{Q}_{L,I,\ U,I}$	QL(I), QU(I), I = 1 or 2 [W]
$\dot{Q}_{VENT,I}$	QVENT(I), I = 1 or 2 [W]
T	TBAR [K]
T_I	T(I), I = 1 or 2 [K]
$T_{L,I}$, $T_{U,I}$	TL(I), TU(I), I = 1 or 2 [K]
$T_{VENT,I}$	TVENT(I), I = 1 or 2 [K]
$\dot{V}_{B,HIGH}$	VBHIGH = VB(1) if $\Delta p \geq 0$, = VB(2) if $\Delta p \leq 0$ [m^3/s]
$\dot{V}_{B,LOW}$	VBLOW = VB(2) if $\Delta p \geq 0$, = VB(1) if $\Delta p \leq 0$ [m^3/s]
$\dot{V}_{EX,MAX}$	VEXMAX [m^3/s]
$\dot{V}_{HIGH}$, $\dot{V}_{LOW}$	VHIGH, VLOW [m^3/s]

$\dot{V}_{\mathrm{HIGH,FLOOD}}$	VHIGHFL [m^3/s]
$\dot{V}_{\mathrm{ST,HIGH}}$	V = VST(1) if $\Delta p > 0$, = VST(2) if $\Delta p < 0$ [m^3/s]
$\dot{V}_{\mathrm{VENT},I}$	VVENT(I), I = 1 or 2 [m^3/s]
w	W [dimensionless]
x	X [dimensionless]
$y_{\mathrm{CEIL},I}$	YCEIL(I), I = 1 or 2 [m]
$y_{\mathrm{LAYER},I}$	YLAY(I), I = 1 or 2 [m]
$y_{\mathrm{REF},I}$	YREF(I), I = 1 or 2 [m]
y_{VENT}	YVENT [m]
γ	1.40
Δp	DELP [$Pa = kg/(m \cdot s^2)$]
$\Delta p_{\mathrm{CUT}}{}^{1/2}$	DPC1D2 [$Pa = kg/(m \cdot s^2)$]
$\Delta p_{\mathrm{FLOOD}}$	DELPFD [$Pa = kg/(m \cdot s^2)$]
$\Delta \rho$	DELDEN [kg/m^3]
δp^*	DPDDPFL [$Pa = kg/(m \cdot s^2)$]
δp_I	DP(I), I = 1 or 2 [$Pa = kg/(m \cdot s^2)$]
$\delta p_{\mathrm{REF},I}$	DPREF(I), I = 1 or 2 [$Pa = kg/(m \cdot s^2)$]
ε	EPS [dimensionless]
ε_p	EPSP [dimensionless]
μ	XMEW [m^2/s]
ρ_{HIGH}	DENHIGH [kg/m^3]
$\bar{\rho}$	DENBAR [kg/m^3]
ρ_I	DEN(I), I = 1 or 2 [kg/m^3]
$\rho_{\mathrm{L},I}$, $\rho_{\mathrm{U},I}$	DENL(I), DENU(I), I = 1 or 2 [kg/m^3]
$\rho_{\mathrm{VENT},I}$	DENVNT(I), I = 1 or 2 [kg/m^3]
σ_1	SIGMA1 [dimensionless]
σ_2	SIGMA2 [dimensionless]

SUBROUTINE *VENTCF2*

```
      SUBROUTINE VENTCF2(
     I    AVENT,CONL,CONU,CP,NPMAX,NPROD,PDATUM,TL,TU,
     I    YCEIL,YREF,YLAY,YVENT,DPREF,EPSP,DENL,DENU,
     O    C,CVENT,XML,XMU,XMVENT,PL,PU,PVENT,P,QL,QU,QVENT,T,TVENT,
     O    DELP,DEN,DENVNT)
      INCLUDE PRECIS.INC
C*BEG
C***    VENTCF - CALCULATION OF THE FLOW OF MASS, ENTHALPY, OXYGEN, AND OTHER
C       PRODUCTS OF COMBUSTION THROUGH A HORIZONTAL VENT JOINING AN UPPER
C       SPACE 1 TO A LOWER SPACE 2. THE SUBROUTINE USES INPUT DATA DESCRIBING THE
C       TWO-LAYER ENVIRONMENT OF INSIDE ROOMS AND THE UNIFORM ENVIRONMENT IN
C       OUTSIDE SPACES.
C***    SUBROUTINE ARGUMENTS
C
C INPUT
C ----
C AVENT       -      AREA OF THE VENT [M**2]
C CONL(K,I)   -      CONCENTRATION OF PRODUCT K IN LOWER LAYER OF AN INSIDE
C                    ROOM I OR UNIFORM CONCENTRATION OF PRODUCT K IN AN
C                    OUTSIDE SPACE I [(UNIT OF PRODUCT)/(KG LAYER)]
C CONL(K,I)   -      CONCENTRATION OF PRODUCT K IN UPPER LAYER OF AN INSIDE
C                    ROOM I OR UNIFORM CONCENTRATION OF PRODUCT K IN AN
C                    OUTSIDE SPACE I [(UNIT OF PRODUCT)/(KG LAYER)]
C CP          -      SPECIFIC HEAT [W*S/(KG*K)]
C NPMAX       -      MAXIMUM ALLOWED NUMBER OF PRODUCTS
C NPROD       -      NUMBER OF PRODUCTS IN CURRENT SCENARIO
C PDATUM      -      DATUM ABSOLUTE PRESSURE [PA = KG/(M*S**2)]
C TL(I)       -      TEMPERATURE OF LOWER LAYER OF AN INSIDE ROOM I OR
C                    TEMPERATURE OF AN OUTSIDE SPACE I [K]
C TU(I)       -      TEMPERATURE OF UPPER LAYER OF AN INSIDE ROOM I OR
C                    TEMPERATURE OF AN OUTSIDE SPACE I [K]
C YCEIL(I)    -      HEIGHT OF CEILING ABOVE DATUM ELEVATION FOR AN INSIDE
C                    ROOM I OR YREF(I) FOR AN OUTSIDE SPACE I [M]
C YREF(I)     -      HEIGHT OF REFERENCE ELEVATION FOR SPACE I ABOVE DATUM
C                    ELEVATION [M]
C YLAY(I)     -      HEIGHT OF LAYER ABOVE DATUM ELEVATION FOR AN INSIDE
C                    ROOM I OR YREF(I) FOR AN OUTSIDE SPACE I [M]
C YVENT       -      HEIGHT OF VENT ABOVE DATUM ELEVATION [M]
C DPREF(I)    -      PRESSURE IN SPACE I AT ITS REFERENCE ELEVATION ABOVE
C                    DATUM ABSOLUTE PRESSURE [PA = KG/(M*S**2)]
C EPSP        -      ERROR TOLERANCE FOR DPREF [DIMENSIONLESS]
C DENL(I)     -      DENSITY OF LOWER LAYER OF AN INSIDE ROOM I OR DENSITY
C                    OF AN OUTSIDE SPACE I [KG/M**3]
C DENU(I)     -      DENSITY OF UPPER LAYER OF AN INSIDE ROOM I OR DENSITY
C                    OF AN OUTSIDE SPACE I [KG/M**3]
C
C OUTPUT
C ----
C C(K,I)      -      CONCENTRATION OF PRODUCT K IMMEDIATELY ABOVE (IN SPACE I = 1)
C                    AND BELOW (IN SPACE I = 2) VENT [(UNIT OF PRODUCT)/(KG LAYER)]
C CVENT(I)    -      CONCENTRATION OF EACH PRODUCT IN THE VENT FLOW COMPONENT
C                    ENTERING SPACE I [(UNIT OF PRODUCT)/(KG OF    VENT FLOW)]
C XML(I)      -      RATE AT WHICH MASS IS ADDED TO THE LOWER LAYER OF AN INSIDE
C                    ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I =1 (I = 2) DUE TO THE
C                    VENT FLOW COMPONENT ENTERING SPACE = 2 (I = 1) [KG/S]
C XMU(I)      -      RATE AT WHICH MASS IS ADDED TO THE UPPER LAYER OF AN
C                    INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I = 1
C                    (I = 2) DUE TO THE VENT FLOW COMPONENT ENTERING SPACE
C                    I = 2 (I = 1) [KG/S]
C XMVENT(I)   -      MASS FLOW RATE IN THE VENT FLOW COMPONENT ENTERING
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C                           SPACE I [KG/S]
C  PL(K,I)          -       RATE AT WHICH PRODUCT K IS ADDED TO THE LOWER LAYER OF
C                           AN INSIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I
C                           = 1 (I = 2) DUE TO THE VENT FLOW CONPONENT ENTERING
C                           SPACE I = 2 (I = 1) [(UNIT OF PRODUCT)/S]
C  PU(K,I)          -       RATE AT WHICH PRODUCT K IS ADDED TO THE UPPER LAYER OF AN IN-
C                           SIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I = 1 (I = 2) DUE TO
C                           THE VENT FLOW COMPONENT ENTERING SPACE I = 2 (I = 1) [(UNIT OF
C                           PRODUCT)/S]
C  PVENT(K,I)       -       FLOW RATE OF PRODUCT K IN THE VENT FLOW COMPONENT
C                           ENTERING SPACE I [(UNIT OF PRODUCT)/S]
C  P(I)             -       ABSOLUTE PRESSURE IMMEDIATELY ABOVE (IN SPACE I = 1)
C                           AND BELOW (IN SPACE I = 2) THE VENT [PA = KG/(M*S**2)]
C  QL(I)            -       RATE AT WHICH ENTHALPY IS ADDED TO THE LOWER LAYER OF AN IN-
C                           SIDE ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I = 1 (I = 2) DUE TO
C                           THE VENT FLOW COMPONENT ENTERING SPACE I = 2 (I = 1) [W]
C  QU(I)            -       RATE OF ENTHALPY ADDITION TO THE UPPER LAYER OF AN INSIDE
C                           ROOM I = 1 (I = 2) OR TO AN OUTSIDE SPACE I = 1 (I = 2) DUE TO VENT
C                           FLOW COMPONENT ENTERING SPACE I = 2 (I = 1) [W]
C  QVENT(I)         -       FLOW RATE OF ENTHALPY IN THE VENT FLOW COMPONENT
C                           ENTERING SPACE I [W]
C  T(I)             -       ABSOLUTE TEMPERATURE IMMEDIATELY ABOVE (IN SPACE I =
C                           1) AND BELOW (IN SPACE I = 2) THE VENT [K]
C  TVENT(I)         -       ABSOLUTE TEMPERATURE OF THE VENT FLOW COMPONENT
C                           ENTERING SPACE I [K]
C  DELP             -       CROSS-VENT PRESSURE DIFFERENCE, P(2) - P(1), [PA = KG/(M*S**2)]
C  DEN(I)           -       DENSITY IMMEDIATELY ABOVE (IN SPACE I = 1) AND BELOW
C                           (IN SPACE I = 2) THE VENT [KG/M**3]
C  DENVNT(I)        -       DENSITY OF THE VENT FLOW COMPONENT ENTERING SPACE I
C                           [KG/M**3]
C*END
C****      NOTE THAT NPMAX2 SHOULD BE BIGGER THAT NPMAX
           PARAMETER (NPMAX2=10)
           DIMENSION CONL(NPMAX2,2), CONU(NPMAX2,2), TL(2), TU(2)
           DIMENSION YCEIL(2), YREF(2), YLAY(2), DPREF(2)
           DIMENSION DENL(2), DENU(2)
           DIMENSION C(NPMAX2,2), CVENT(NPMAX2,2), XML(2), XMU(2)
           DIMENSION XMVENT(2)
           DIMENSION PL(NPMAX2,2), PU(NPMAX2,2), PVENT(NPMAX2,2), P(2)
           DIMENSION QL(2),QU(2)
           DIMENSION QVENT(2), T(2), TVENT(2), DEN(2), DENVNT(2)
           DIMENSION DP(2),VB(2),VST(2), VVENT(2)
           PARAMETER (GAM=1.40D0)
           DATA IFIRST/0/
           SAVE IFIRST,GAMCUT,GAMMAX
           PARAMETER (G=9.80D0)
           PARAMETER (PI=3.141592654D0)
           PARAMETER (SIGMA2=1.045D0)
           PARAMETER (XM3=-0.7070D0)
           GR=0.D0
           VHIGHFL=0.D0
           DELPFL=0.D0
           DO 5 I=1,2
           VST(I)=0.D0
           VB(I)=0.D0
           QVENT(I)=0.D0
           XMVENT(I)=0.D0
           DO 2 NP=1,NPROD
           PVENT(NP,I)=0.D0
   2       CONTINUE
   5       CONTINUE
C***       THE FOLLOWING CODE SEGMENT COMPUTES CONSTANTS REQUIRED BY VENTCF2.
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```
C***    IT IS EXECUTED THE FIRST TIME VENTCF IS CALLED.
        IF(IFIRST.EQ.0)THEN
                IFIRST = 1
                GAMCUT = (2.0D0/(GAM+1.0D0))**(GAM/(GAM-1.0D0))
                ZZZ=GAM*((2.0D0/(GAM+1.0D0))**((GAM+1.0D0)/(GAM-1.0D0)))
                GAMMAX = DSQRT(ZZZ)
        ENDIF
C***    1. AND 2. CALCULATE THE P(I), DELP, THE OTHER PROPERTIES ADJACENT TO THE
C***    TWO SIDES OF THE VENT, AND DELDEN.
        DO 10 I = 1, 2
                IF(YREF(I).LE.YVENT.AND.YVENT.LE.YLAY(I))THEN
C***    VENT IS AT OR BELOW REFERENCE ELEVATION IN SPACE I. IF SPACE I IS AN INSIDE
C***    ROOM, THEN BOTH THE VENT AND THE LAYER INTERFACE ARE AT FLOOR ELEVATION.
                        DP(I) = - G*DENL(I)*(YVENT - YREF(I))
                ELSE
C***    THE VENT IS ABOVE THE REFERENCE ELEVATION IN SPACE I.
C***    IF SPACE I IS AN INSIDE ROOM THEN THE VENT IS AT THE
C***    CEILING.
                        DP(I) = - G*DENL(I)*(YLAY(I)-YREF(I))
   $                  - G*DENU(I)*(YVENT-YLAY(I))
                ENDIF
                P(I) = DPREF(I) + DP(I) + PDATUM
10      CONTINUE
C***    DELP IS PRESSURE IMMEDIATELY BELOW THE VENT LESS PRESSURE
C***    IMMEDIATELY ABOVE THE VENT.
        DELP = (DPREF(2)-DPREF(1))+(DP(2)-DP(1))
        DO 30 I = 1, 2
                DEN(I) = 0.0D0
                T(I) = 0.0D0
                DO 22 K = 1, NPROD
                        C(K,I) = 0.0D0
22              CONTINUE
                IF(((YVENT.EQ.YREF(I)).AND.((YLAY(I)-YREF(I)).LT.0.D0))
   $     .OR.((YVENT.EQ.YCEIL(I)).AND.((YCEIL(I)-YLAY(I))
   $                             .GT.0.D0)))THEN
                DEN(I) = DENU(I)
                        T(I) = TU(I)
                        DO 24 K = 1, NPROD
                                C(K,I) = CONU(K,I)
24                      CONTINUE
                ELSE
                        DEN(I) = DENL(I)
                        T(I) = TL(I)
                        DO 26 K = 1, NPROD
                                C(K,I) = CONL(K,I)
26                      CONTINUE
                ENDIF
30      CONTINUE
C***    DELDEN IS DENSITY IMMEDIATELY ABOVE THE VENT LESS DENSITY
C***    DENSITY IMMEDIATELY BELOW THE VENT
        DELDEN = DEN(1) - DEN(2)
C***    3. CALCULATE VST(I), THE "STANDARD" VOLUME RATE OF FLOW THROUGH THE VENT
C***    INTO SPACE I. CALCULATE VST(I) IF DELP = 0.
        IF(DELP.EQ.0.0D0)THEN
                VST(1) = 0.0D0
                VST(2) = 0.0D0
        ENDIF
        IF(DELP.EQ.0.D0) GOTO 32
C***    CALCULATE VST(I) FOR NONZERO DELP
        IF(DELP.GT.0.0D0)THEN
                VST(2) = 0.0D0
                RHO = DEN(2)
```

```
               EPS = DELP/P(2)
          ENDIF
          IF(DELP.LT.0.0D0)THEN
               VST(1) = 0.0D0
               RHO = DEN(1)
               EPS = -DELP/P(1)
          ENDIF
          X = 1.0D0 - EPS
          COEF = 0.60D0 + 0.25D0*EPS
          XO = 1.0D0
          EPSCUT = EPSP*MAX(XO,DPREF(1),DPREF(2))
          EPSCUT = DSQRT(EPSCUT)
          SRDELP = DSQRT(DABS(DELP))
          FNOISE = 1.0D0
          IF((SRDELP/EPSCUT).LE.130.D0)THEN
               FNOISE = 1.0D0 - DEXP(-SRDELP/EPSCUT)
C***      NOTE: IF SINGLE PRECISION THEN USE 65. INSTEAD OF 130.
          ENDIF
          IF(EPS.LE.0.1D-5)THEN
               W = 1.0D0 - 0.75D0*EPS/GAM
          ELSE
               IF(EPS.LT.GAMCUT)THEN
                    GG = X**(1.0D0/GAM)
                    FF = DSQRT((2.0D0*GAM/(GAM-1.0D0))*GG*GG*
     $                                                 (1.0D0-X/GG))
               ELSE
                    FF = GAMMAX
               ENDIF
                    W = FF/DSQRT(EPS+EPS)
          ENDIF
          V = FNOISE*COEF*W*DSQRT(2.0D0/RHO)*AVENT*SRDELP
          IF(DELP.GT.0.0D0)VST(1) = V
          IF(DELP.LT.0.0D0)VST(2) = V
   32 CONTINUE
C***      4. WHEN CROSS-VENT DENSITY CONFIGURATION IS UNSTABLE, I.E.,DELDEN > 0,
C***      THEN CALCULATE THE VENT FLOW ACCORDING TO: COOPER, L.Y., COMBINED PRES-
C***      SURE- AND BUOYANCY-DRIVEN FLOW THROUGH A HORIZONTAL VENT, NISTIR 5384,
C***      NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, GAITHERSBURG MD. FOR
C***      STABLE CONFIGURATION, GO TO 5. AND CALCULATE FLOW WITH STANDARD MODEL.
          IF(DELDEN.LE.0.0D0) GOTO 35
C***      FOR UNSTABLE CONFIGURATION, NOW CALCULATE THE COMBINED PRESSURE- AND
C***      BUOYANCY-DRIVEN VOLUME VENT FLOW RATES FROM THE HIGH-TO-LOW AND FROM
C***      THE LOW-TO-HIGH SIDES OF THE VENT, VBHIGH AND VBLOW, RESPECTIVELY. FROM
C***      THESE, THEN CALCULATE THE COMBINED PRESSURE- AND BUOYANCY-DRIVEN VOL-
C***      UME FLOW RATES, VB(I), THROUGH THE VENT INTO SPACE I.
          TBAR=(T(1)+T(2))/2.D0
          DENBAR=(DEN(1)+DEN(2))/2.D0
          XMEW=(0.04128D-7)*DENBAR*(TBAR**2.5D0)/(TBAR+110.4D0)
          EPSDEN=DELDEN/DENBAR
          D=DSQRT(4.D0*AVENT/PI)
          GR=2.D0*G*(D**3)*EPSDEN/((XMEW/DENBAR)**2.D0)
          IF(DELP.GT.0.D0) EPSDEN=-EPSDEN
          VHIGHFL=0.1754D0*AVENT*DSQRT(2.D0*G*D*DABS(EPSDEN))*
     1                                                 DEXP(0.5536D0*EPSDEN)
          DELPFL=0.2427D0*(4.D0*G*DABS(EPSDEN*DENBAR)*D)*(1.D0+EPSDEN/2.D0)*
     1                                                 DEXP(1.1072D0*EPSDEN)
          DPDDPFL=DABS(DELP)/DELPFL
          SIGMA1=FNOISE*COEF*W/0.1780D0
          IF(DPDDPFL.GE.1.D0)THEN
               VBLOW=0.D0
               VBHIGH=VHIGHFL*(1.D0-(SIGMA2**2.D0)+
     1              DSQRT(SIGMA2**4.D0+(SIGMA1**2.D0)* (DPDDPFL-1.D0)))
```

```
        ELSE
                VEXMAX=0.055D0*(4.D0/PI)*AVENT*DSQRT(G*D*DABS(EPSDEN))
                XM=(SIGMA1/SIGMA2)**2.D0-1.D0
                VBLOW=VEXMAX*(((1.D0+XM3/2.D0)*((1.D0-DPDDPFL)**2)-
     1                                          (2.D0+XM3/2.D0)*(1.D0-DPDDPFL))**2.D0)
                IF(DPDDPFL.EQ.0.D0)THEN
                        VBHIGH=VBLOW
                ELSE
                        VBHIGH=VBLOW+
     1          (XM-DSQRT(1.D0+(XM**2.D0-1.D0)*(1.D0-DPDDPFL)))*
     1                                          VHIGHFL/(XM-1.D0)
                ENDIF
        ENDIF
        IF(DELP.GT.0.D0)THEN
                VB(1)=VBHIGH
                VB(2)=VBLOW
        ELSE
                VB(1)=VBLOW
                VB(2)=VBHIGH
        ENDIF
C***    5. CALCULATE VVENT(I), VOLUME RATE OF FLOW THROUGH THE VENT INTO SPACE I.
35      CONTINUE
        IF(DELDEN.LE.0.0D0)THEN
                VVENT(1) = VST(1)
                VVENT(2) = VST(2)
        ELSE
                IF((0.D0.LT.GR).AND.(GR.LT.2.D7))THEN
                VVENT(1)=VST(1)+(GR/2.D7)*(VB(1)-VST(1))
                VVENT(2)=VST(2)+(GR/2.D7)*(VB(2)-VST(2))
                        ELSE
                        VVENT(1)=VB(1)
                        VVENT(2)=VB(2)
                ENDIF
        ENDIF
C***    6. CALCULATE THE VENT FLOW PROPERTIES
        DENVNT(1) = DEN(2)*P(1)/P(2)
        DENVNT(2) = DEN(1)*P(2)/P(1)
        TVENT(1) = T(2)
        TVENT(2) = T(1)
        DO 50 K = 1, NPROD
                CVENT(K,1) = C(K,2)
                CVENT(K,2) = C(K,1)
50      CONTINUE
C***    7. CALCULATE THE VENT MASS FLOW RATES
        DO 60 I = 1,2
                XMVENT(I) = DENVNT(I)*VVENT(I)
60      CONTINUE
C***    8. CALCULATE THE REST OF THE VENT FLOW RATES
        DO 70 I=1,2
                QVENT(I) = XMVENT(I)*CP*TVENT(I)
                DO 65 K = 1, NPROD
                        PVENT(K,I) = XMVENT(I)*CVENT(K,I)
65              CONTINUE
70      CONTINUE
C***    9. CALCULATE THE RATE AT WHICH THE VENT FLOWS ADD MASS, ENTHALPY, AND
C***    PRODUCTS TO THE LAYERS OF THE SPACES FROM WHICH THEY ARE EXTRACTED.
C***    FIRST TREAT LAYERS OF SPACE 1 (I=1, J=2) AND THEN SPACE 2 (I=2, J=1).
        DO 95 I = 1, 2
                IF (I.EQ.1)THEN
                        J = 2
                ELSE
                        J = 1
```

```
                    ENDIF
                    IF(((YVENT.EQ.YREF(I)).AND.((YLAY(I)-YREF(I)).LT.0.D0))
     $        .OR.((YVENT.EQ.YCEIL(I)).AND.((YCEIL(I)-YLAY(I))
     $                            .GT.0.D0)))THEN
                        XMU(I) = -XMVENT(J)
                        XML(I) = 0.0D0
                        QU(I) = -QVENT(J)
                        QL(I) = 0.0D0
                        DO 75 K = 1, NPROD
                            PU(K,I) = -PVENT(K,J)
                            PL(K,I) = 0.0D0
75                      CONTINUE
                        IF(DABS(YREF(I)-YCEIL(I)).LT.0.0001D0)THEN
                            XML(I) = XMU(I)
                            QL(I) = QU(I)
                            DO 80 K = 1, NPROD
                                PL(K,I) = PU(K,I)
80                          CONTINUE
                        ENDIF
                        ELSE
                        XML(I) = -XMVENT(J)
                        XMU(I) = 0.0D0
                        QL(I) = -QVENT(J)
                        QU(I) = 0.0D0
                        DO 85 K = 1, NPROD
                            PL(K,I) = -PVENT(K,J)
                            PU(K,I) = 0.0D0
85                      CONTINUE
                        IF(DABS(YREF(I)-YCEIL(I)).LT.0.0001D0)THEN
                            XMU(I) = XML(I)
                            QU(I) = QL(I)
                            DO 90 K = 1, NPROD
                                PU(K,I) = PL(K,I)
90                          CONTINUE
                        ENDIF
                    ENDIF
95      CONTINUE
        RETURN
        END
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REFERENCES

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